Desktop Application

Solar Panel Equivalent Circuit Parameters Extractor

Introduction and User Manual

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1 INTRODUCTION

1.1 The need for the solar panel's equivalent circuit parameters

Solar panels have been used to harness the solar energy as a type of clean energy and are becoming more and more widely used. According to Solar Industry Research Data [1], the installed solar capacity in the U.S. has been continuously increasing in the recent ten years and has reached a value more than 110,000 MW by the third quarter of 2021.

The need for the solar panel's equivalent circuit parameters arises when simulating circuits containing solar panel models. To convert and transfer the solar energy obtained from the solar panels to the load, the dc power as the output of the solar panel is usually transformed into ac power using power electronic converters, so that the power can be transferred using the ac power grid. When designing such converters and the associated controllers, simulation tools such as Simulink, PLECS, PSpice, etc., are usually used to perform some initial studies of the design specifics of the converters and their controllers. If these simulations tools are used to design the converters for the solar panels, one must obtain the equivalent circuit and its parameters for the solar panels and put these into the simulation software. Unfortunately, the solar panel's equivalent circuit parameters are not provided directly on the manufacture's datasheet and cannot be measured directly, and some of these parameters are dependent on the environment parameters such as the solar irradiance and the temperature.

To extract the solar panel's equivalent circuit parameters, a commonly used method is to make measurements of the current and the voltage at the terminal of a solar panel, and use the solar panel's I-V characteristic equation and nonlinear regression. This is a viable method, but it requires a "hard copy" of a solar panel, and usually obtaining a solar panel is not free. If one needs to get the equivalent circuit parameters for different solar panels of different types, using this nonlinear regression method, one needs to spend much money obtaining all the solar panels that one needs. In the initial designing stage, such a cost is not desirable. The question is, is there a cheaper way to obtain the equivalent circuit parameters of a solar panel?

In the course, EEE-598 Renewable Energy Systems, in Arizona State University, a graphical method was introduced in the class to make extracting the solar panel's equivalent circuit parameters possible without obtaining a solar panel. The philosophy is that whenever the I-V curve in the standard test condition (STC, 25°C and 1000 W/m^2 solar irradiance) is also provided on the datasheet by the manufacture, the equivalent circuit parameters can be extracted only by solving a set of nonlinear equations. The essence of this method will be presented later in the next chapter. To use this method, the user needs to use some graphical tools in PowerPoint to approximate the tangents of the I-V curve, a pen or a pencil, and some papers (or Notepad in Windows) to record the coordinates and angles of the tangents, and MATLAB (or Mathcad) to solve nonlinear equations. There are some non-trivial calculation rules to take into consideration the fact that 1 inch on the I-V curve plot printed on the datasheet does not necessarily represent 1 A or 1 V.

While this graphical method seems free at first glance, it processes some disadvantages. It easier for the user to make mistakes in the calculation, because the user uses a pen and papers and the non-trivial calculation rules. Plus, MATLAB and Mathcad are not free software. They are only free for students whose institutions have bought the license. Plus, when obtaining the equivalent circuit parameters for several types of solar panels, the user must use several tools and switch between them. This can sometimes be inconvenient.

There is a need for an application that makes it possible to extract the equivalent circuit parameters of a solar panel as conveniently and accurately as possible, and that is free. Therefore, this desktop application, Solar Panel Equivalent Circuit Parameters Extractor, was developed. This application is sometimes simply called "the application" in this introduction and user manual. With this application, the user can extract the equivalent circuit parameters using the graphical method much more easily, and it is free of charge.

1.2 The overview

This introduction and user manual presents the math that makes the application work, the steps to use the application, and the steps to perform validation of the results. If the reader is not familiar with the graphical method, after reading this manual, the user will know how to use the application and have an idea about the math of the graphical method behind the application.

Chapter 2 shows the math that makes the application work. Chapter 3 presents the detailed steps that are used to extract of the equivalent circuit parameters using this application. Chapter 4 shows how to perform results validation.

If one hopes to learn how to use the application as soon as possible, please feel free to start reading from Chapter 3.

2 MATHEMATICS

2.1 The theoretical background of the application

To use the application more efficiently, the user is expected to know the equivalent circuit model of the solar panel and the solar panel's I-V characteristic equation. This chapter is used to refresh the user's memory or present this theoretical background for new beginners who are unfamiliar with the theory of solar panels/cells. If the user is already familiar with these, please feel free jump to Chapter 3 to see how to use the application.

2.2 The solar panel's equivalent circuit model

The solar panel's equivalent circuit model is shown in Fig. 2.1, which is a modified figure from Wikipedia [2] for a single solar cell.

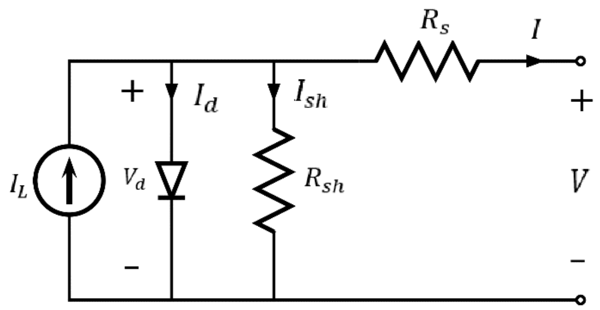

Fig. 2.1 The solar panel equivalent circuit

In Fig. 2.1, I_L is the photogenerated current, V_d is the voltage across the diode, I_d is the current going through the diode, R_{sh} is the shunt resistance of the solar panel, R_s is the series resistance of the solar panel, I_{sh} is the current going through the shunt resistance, V and I are the voltage and the current seen at the equivalent circuit's terminal.

It is assumed that all the solar cells in a single solar panel are identical for it makes the analysis much easier. After using KVL and KCL, and the diode's nonlinear I-V characteristic equation, the I-V characteristic equation of the solar panel is easily obtained as,

$$I = I_L - I_o\left(e^{\frac{V+IR_s}{N_{cell}aV_T}} - 1\right) - \frac{V + IR_s}{R_{sh}} \qquad (2.1)$$

where a is the diode's ideality factor, I_o is the diode's reverse saturation current, N_{cell} is the number of solar cells per solar panel, and V_T is the thermal voltage of a single solar cell,

$$V_T = \frac{kT}{q_e} \qquad (2.2)$$

where k is Boltzmann constant, T is the temperature (with its unit as K), and q_e is the charge of an electron.

In (2.1), the equivalent circuit parameters to be extracted are: I_L, I_o, a, R_s, and R_{sh}. With the I-V characteristic equation, we can look into how these parameters can be extracted using the graphical method in the next section.

2.3 The graphical method

2.3.1 Differentiating the I-V characteristic equation

There are five unknown parameters to be extracted. On the datasheet provided by the manufacturer, there are usually only three datapoints on the I-V curve that are directly available, which are the short circuit current, the open circuit voltage, and the optimal operating point (the terminal voltage and current where the maximum output power is obtained) in the STC. To extract the parameters, we also need to use the information represented by the slope, dI/dV, of the tangent of the I-V curve presented on the datasheet provided by the manufacture.

Considering that V and I are variables and assuming the condition in the implicit function theorem [3] that guarantees dI/dV exists is satisfied, differentiating (2.1) on both sides yields,

$$\frac{dI}{dV} = -\frac{I_o}{N_{cell}aV_T}\left(e^{\frac{V+IR_s}{N_{cell}aV_T}}\left(1+\frac{dI}{dV}\right)\right) - \frac{1}{R_{sh}}\left(1+\frac{R_s}{R_{sh}}\frac{dI}{dV}\right) \tag{2.3}$$

2.3.2 Extracting I_L

It is easy to extract I_L by using some reasonable assumptions. For a solar panel that is not defective, $R_s \ll R_{sh}$ and $I_o \ll I_{sc}$, where I_{sc} is the short circuit current. On the datasheet, the short circuit current at STC, I_{sc_STC}, and the short circuit current's temperature coefficient K_I are all available. It is assumed that K_I's unit is 1/°C. With (2.1) and the assumptions that $R_s \ll R_{sh}$ and $I_o \ll I_{sc}$, the photogenerated current, I_L, in the working environment temperature can be obtained as,

$$I_L = I_{sc\_STC}(1 + K_I \Delta T)\frac{G}{G_{STC}} \tag{2.4}$$

where G is the solar irradiance in the working environment, G_{STC} is the solar irradiance in the STC (W/m^2), and ΔT is the temperature difference between the working environment and the STC.

2.3.3 Extracting R_{sh}

Based on the assumption that $R_s \ll R_{sh}$, and for a solar panel that is not defective,

$$\frac{I_o}{N_{cell}aV_T}\left(e^{\frac{V+IR_s}{N_{cell}aV_T}}\left(1+\frac{dI}{dV}\right)\right) \approx 0 \tag{2.5}$$

at the short circuit condition, one can obtain that,

$$R_{sh} = -\frac{1}{\left.\frac{dI}{dV}\right|_{short\ circuit}} \tag{2.6}$$

using (2.3).

2.3.4 Extracting a, I_o, and R_s

To extract the parameters, a, I_o, and R_s, one needs to solve a nonlinear system of equation. To avoid unnecessarily reinventing the wheel, the solver chosen for solving the nonlinear system is SciPy's fsolve function [4].

To obtain the first nonlinear equation, one must be cautious. The diode parameter I_o is more sensitive to the working environment's temperature. Because the open circuit voltage, the short circuit current, and the optimal operating point voltage and current data given in the datasheet are all for STC, we need to assume the working environment condition is STC first and then adapt the extracted parameter , I_o , to the working environment condition.

The first equation is obtained by applying the open circuit voltage to the I-V characteristic equation, (2.1),

$$f_1(a, R_s, I_o) = I_o - \frac{I_{sc\_STC} - \frac{V_{oc\_STC}}{R_{sh}}}{e^{\frac{V+IR_s}{N_{cell}aV_T}} - 1} = 0 \tag{2.7}$$

where V_{oc_STC} is the open circuit voltage at STC. It is assumed that at STC, $I_L \approx I_{sc\_STC}$.

The second equation is obtained by applying the optimal operating point at STC to (2.1),

$$f_2(a, R_s, I_o) = I_{mp} - I_{sc\_STC} + I_o\left(e^{\frac{V_{mp}+I_{mp}R_s}{N_{cell}aV_T}} - 1\right) + \frac{V_{mp} + I_{mp}R_s}{R_{sh}} = 0 \tag{2.8}$$

Before starting to get the third equation, one can observe the equivalent circuit in Fig. 2.1 and conclude that in the open circuit condition, the majority of the photogenerated current, $I_L \approx I_{sc\_STC}$, must go through the diode, and I_o is small enough, therefore,

$$I_{sc\_STC} \approx I_o e^{\frac{V_{oc\_STC}}{N_{cell} a V_T}} \tag{2.9}$$

Using (2.9), the third equation is obtained by applying the open circuit voltage to (2.3) and assuming $R_{sh} \gg \frac{V_T}{I_{sc\_STC}}$,

$$f_3(a, R_s, I_o) = R_s + \frac{1}{\left.\frac{dI}{dV}\right|_{open\ circuit}} + \frac{V_V}{I_{sc\_STC}} \tag{2.10}$$

To summarize, the three equations that needs to be solved together to extract a, R_s, and I_o are,

$$f_1(a, R_s, I_o) = I_o - \frac{I_{sc\_STC} - \frac{V_{oc\_STC}}{R_{sh}}}{e^{\frac{V + IR_s}{N_{cell} a V_T}} - 1} = 0 \tag{2.11}$$

$$f_2(a, R_s, I_o) = I_{mp} - I_{sc\_STC} + I_o \left(e^{\frac{V_{mp} + I_{mp} R_s}{N_{cell} a V_T}} - 1 \right) + \frac{V_{mp} + I_{mp} R_s}{R_{sh}} = 0 \tag{2.12}$$

$$f_3(a, R_s, I_o) = R_s + \frac{1}{\left.\frac{dI}{dV}\right|_{open\ circuit}} + \frac{V_V}{I_{sc\_STC}} = 0 \tag{2.13}$$

After I_o is solved at the STC, it needs to be adapted into the working environment. The effect of a change in I_o is reflected in the change in V_{oc}, so the adaption is performed by using,

$$I_o = \frac{I_{sc} - \frac{V_{oc}}{R_{sh}}}{e^{\frac{V + IR_s}{N_{cell} a V_T}} - 1} \tag{2.14}$$

where I_{sc} and V_{oc} at the working environment can be found using,

$$I_{sc} = I_{sc\_STC}(1 + K_I \Delta T) \tag{2.15}$$

$$V_{oc} = V_{oc\_STC}(1 + K_V \Delta T) \tag{2.16}$$

where K_V is the temperature coefficient of open circuit voltage with its unit as 1/°C.

At this moment, the reader may wonder how to obtain $\frac{dI}{dV}$ at the short circuit condition and the open circuit condition. This is done by using the application and is explained in the next chapter.

Having known the mathematics for extracting the solar panel's equivalent circuit parameters, the user is ready to use the application efficiently. The steps for extracting the parameters using the application are presented in the next chapter.

3 HOW TO USE THE APPLICATION

In this chapter, a detailed step-by-step instruction for using the application is presented. To show the user how to extract the solar panel's equivalent circuit parameters, the datasheet [5] of the TSM-290 PC/PA14 solar panel manufactured by Trinasolar is used as the example. A screen capture of the datasheet is shown in Fig. 3.1. The operating system that is used make the screen captures in this work is Windows 10.

ELECTRICAL DATA @ STC	TSM-280 PC/PA14	TSM-285 PC/PA14	TSM-290 PC/PA14	TSM-295 PC/PA14
Peak Power Watts-P_{MAX} (Wp)	280	285	290	295
Power Output Tolerance-P_{MAX} (%)	0/+3	0/+3	0/+3	0/+3
Maximum Power Voltage-V_{MP} (V)	35.4	35.6	36.1	36.6
Maximum Power Current-I_{MPP} (A)	7.91	8.02	8.04	8.07
Open Circuit Voltage-Voc (V)	44.4	44.7	44.9	45.2
Short Circuit Current-Isc (A)	8.41	8.50	8.53	8.55
Module Efficiency η_m (%)	14.4	14.7	14.9	15.2

Values at Standard Test Conditions STC (Air Mass AM1.5, Irradiance 1000W/m², Cell Temperature 25°C).
Power measurement tolerance: ±3%

ELECTRICAL DATA @ NOCT	TSM-280 PC/PA14	TSM-285 PC/PA14	TSM-290 PC/PA14	TSM-295 PC/PA14
Maximum Power-P_{MAX} (Wp)	204	207	211	214
Maximum Power Voltage-V_{MP} (V)	32.0	32.1	32.6	33.0
Maximum Power Current-I_{MPP} (A)	6.37	6.46	6.47	6.48
Open Circuit Voltage (V)-Voc (V)	40.6	40.7	40.9	41.2
Short Circuit Current (A)-Isc (A)	6.85	6.93	6.97	7.00

NOCT: Irradiance at 800W/m², Ambient Temperature 20°C, Wind Speed 1m/s.
Power measurement tolerance: ±3%

MECHANICAL DATA	
Solar cells	Multicrystalline 156 × 156mm (6 inches)
Cell orientation	72 cells (6 × 12)
Module dimensions	1956 × 992 × 40mm (77 × 39.05 × 1.57 inches)
Weight	27.6kg (60.8 lb)
Glass	High transparency solar glass 4.0mm (0.16 inches)
Frame	Anodized aluminium alloy
J-Box	IP 67 rated
Cables	Photovoltaic Technology cable 4.0mm² (0.006 inches²), 1250mm (49.2 inches)
Connector	MC4

Fig. 3.1 The datasheet of TSM-290 PC/PA14 solar panel

Let’s open the application and get familiar with the GUI. When the application is opened, the user should see the main window that looks like Fig. 3.2.

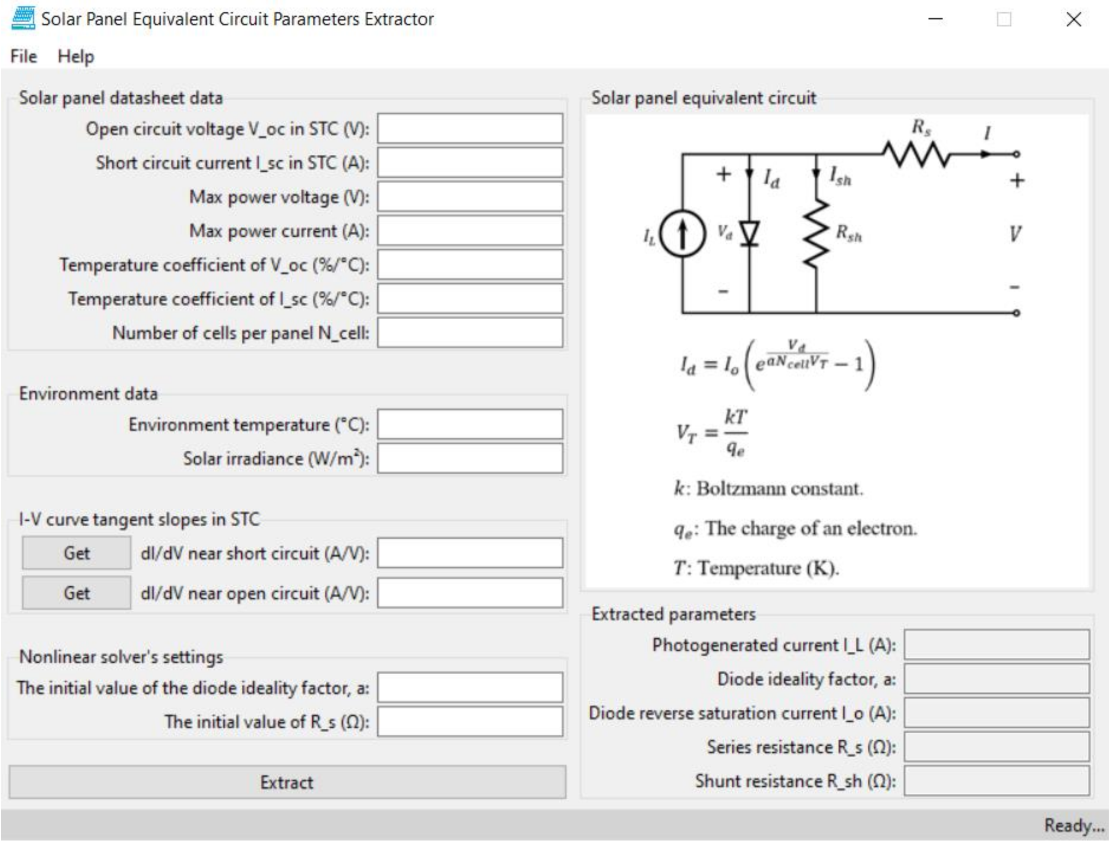

Fig. 3.2 The main window

On the interface shown in Fig. 3.2, there are two columns in the main area. The left column has four sections. In the left column, from the top to the bottom, the first section is for entering the data from the datasheet, the second section is for the environment’s data determined by the user, the third section is for the slopes of the I-V curve, and the last section is for the initial values. Then there is the “Extract” button. The right column has a figure of an equivalent circuit diagram of the solar panel, and the output section for the extracted parameters.

At the top of the window, there is a menu bar and at the bottom of the winder there is a bar showing the execution state of the program.

Let's start with the first step: preprocessing the I-V curve plot provided on the datasheet.

3.1 Step 1. Preprocess the I-V curve plot

The screen capture of the I-V curve shown on the datasheet is presented in Fig. 3.3. The user is only interested in the curve corresponding to 1000 W/m^2, since this is the solar irradiance in the STC.

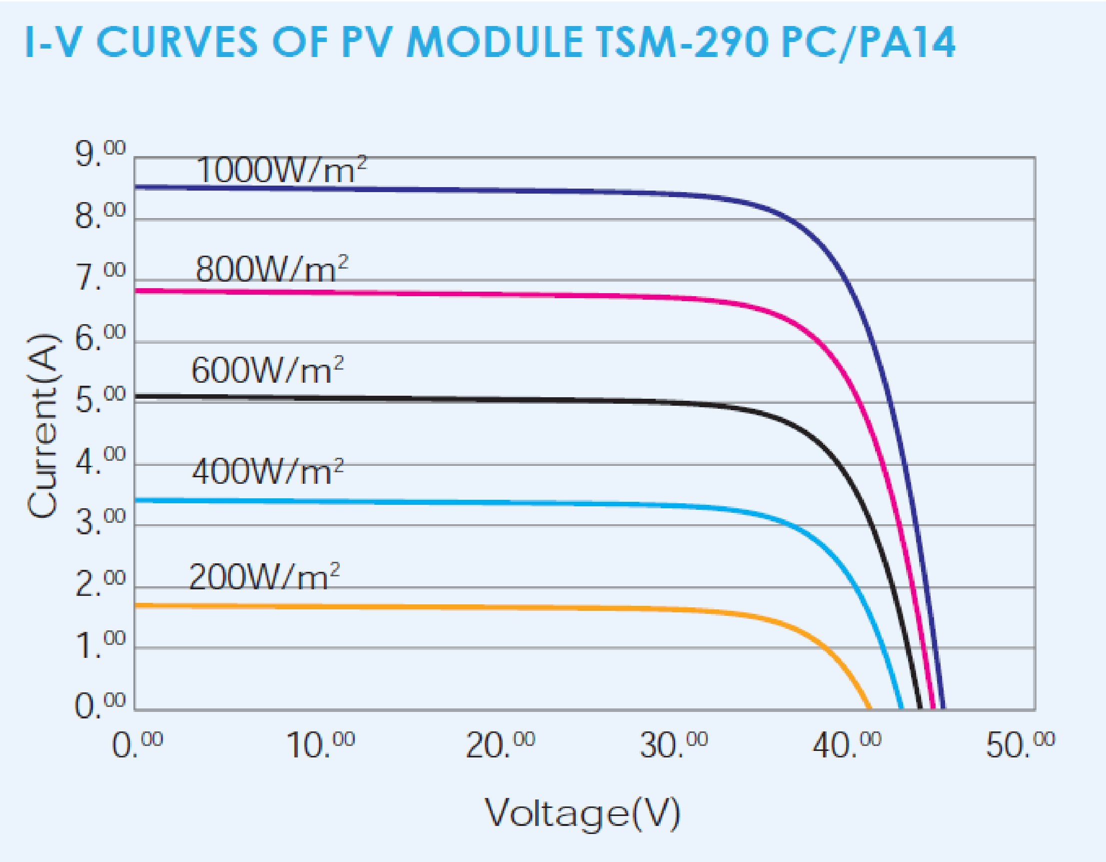

Fig. 3.3 The I-V curve plot of TSM-290 PC/PA14 solar panel

Using a graphical tool that is built-in to the operating system that the user is using, for example, Paint in Windows 10, draw a vertical line corresponding to Voltage = 10 V, shown in Fig. 3.4, and save this marked figure.

Take another two screen captures or enlarge and clip Fig. 3.4 around the short circuit condition and the open circuit condition, shown in Fig. 3.5 and Fig. 3.6, and save the new figures to use later.

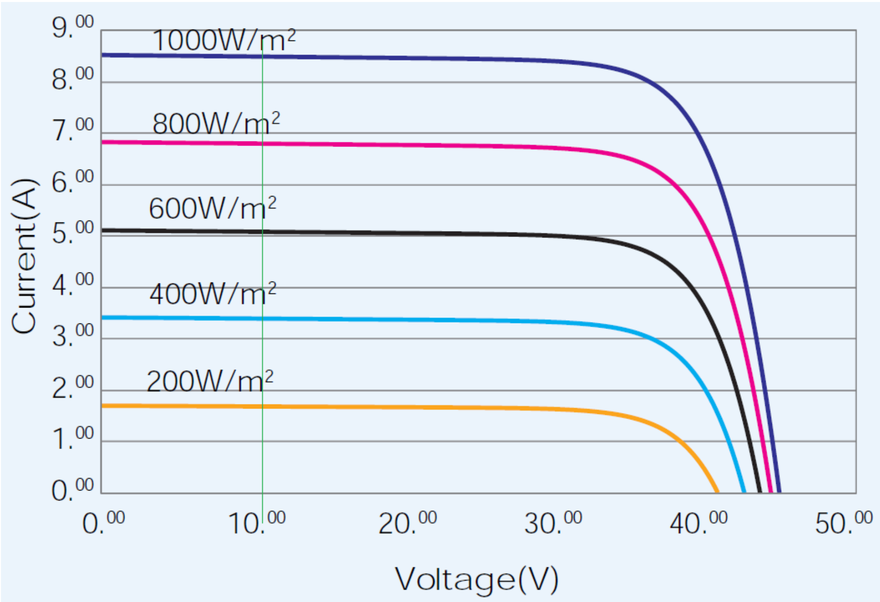

Fig. 3.4 The I-V curve plot of TSM-290 PC/PA14 solar panel, marked

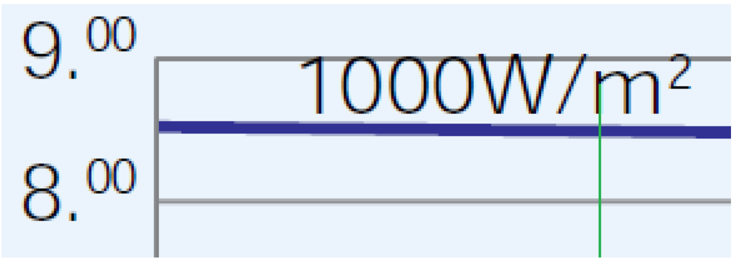

Fig. 3.5 The I-V curve near the short circuit condition

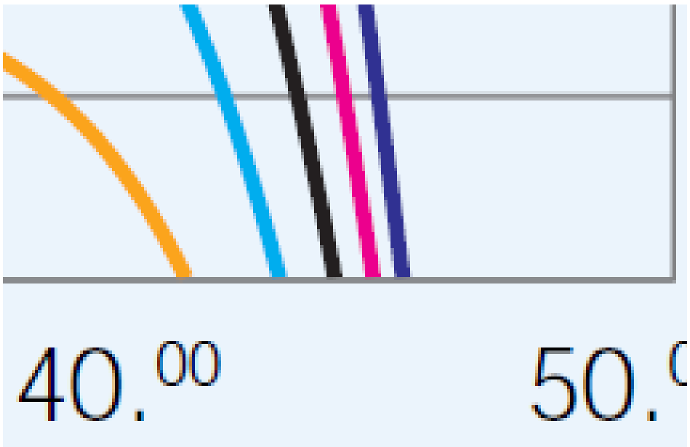

Fig. 3.6 The I-V curve near the open circuit condition

Now, the user has all the figures that are needed to extract the equivalent circuit's parameters.

3.2 Step 2. Enter the data from the datasheet to the application's GUI

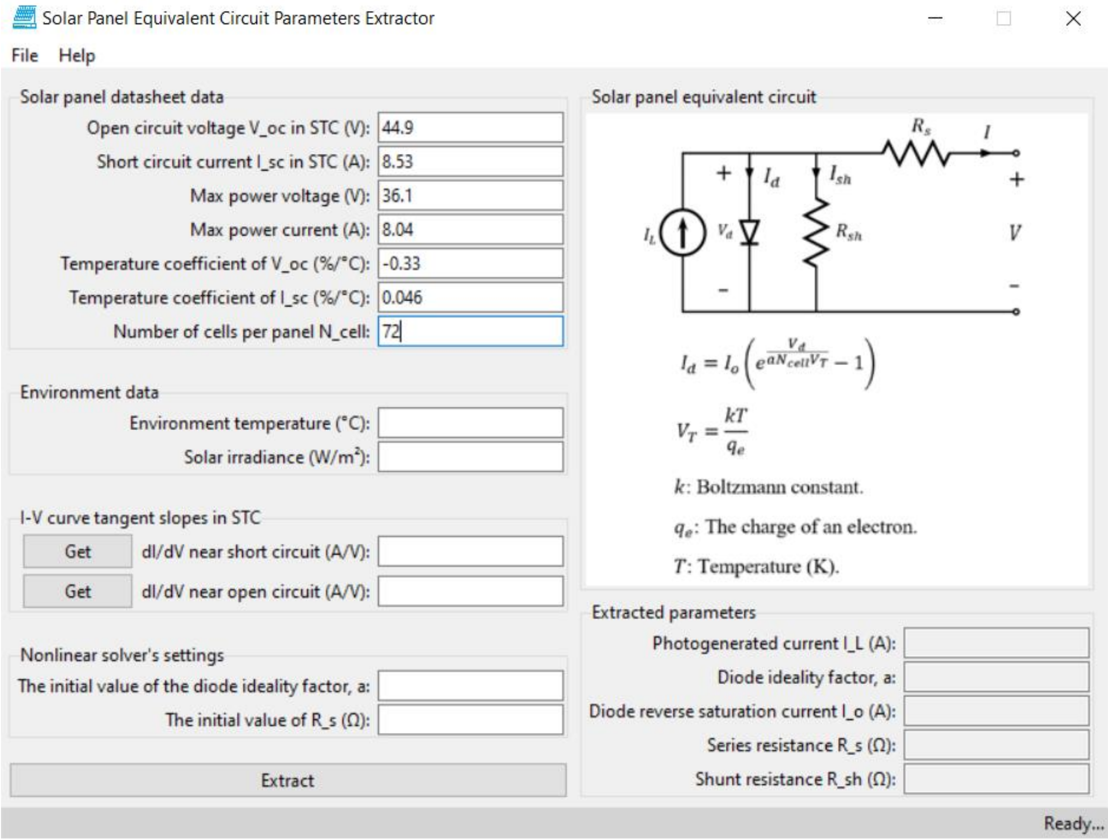

Fig. 3.7 Enter the data from the datasheet

After obtaining the figures that are needed, the user should enter the data such as the open circuit voltage, the short circuit current, temperature coefficients, etc., provided on the datasheet, and the GUI should look like Fig. 3.7.

3.3 Step 3. Enter the data of the environment

The user needs to enter the environment's temperature and the solar irradiance. To make it easier for validation of the extraction results later, use 1000 W/m^2 and 20 °C for now. Now, the GUI should look like Fig. 3.8.

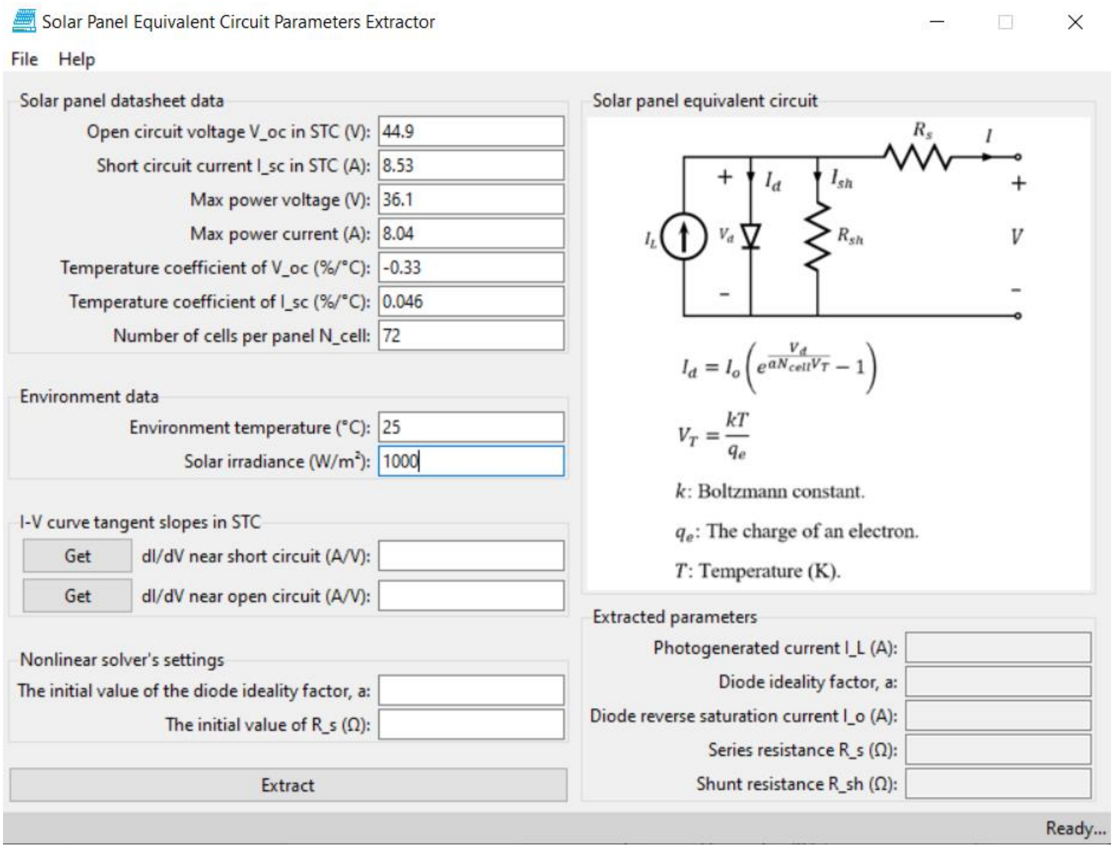

Fig. 3.8 Enter the environment data

3.4 Step 4. Get the slope of the tangent of the I-V curve

As described in Section 2.3, the derivative dI/dV's values at the short circuit condition and the open circuit condition are needed to extract the equivalent circuit's parameters. If the user already has these values, the user can enter them in the GUI. If these values are not available to the user, they can be easily approximated using the built-in graphical tool of the application, described in this section. To approximate dI/dV's value near the short circuit condition, click the "Get" button corresponding to the short circuit condition, and the window shown in Fig. 3.9 should open.

There are two cursors shown in Fig. 3.9, represented by crossing dotted lines. The blue cursor is Cursor 1, and the red cursor is Cursor 2. The active cursor can be chosen using the radio buttons on the right side of the window. The green solid line connecting the two cursors is used to approximate the tangent of the I-V curve.

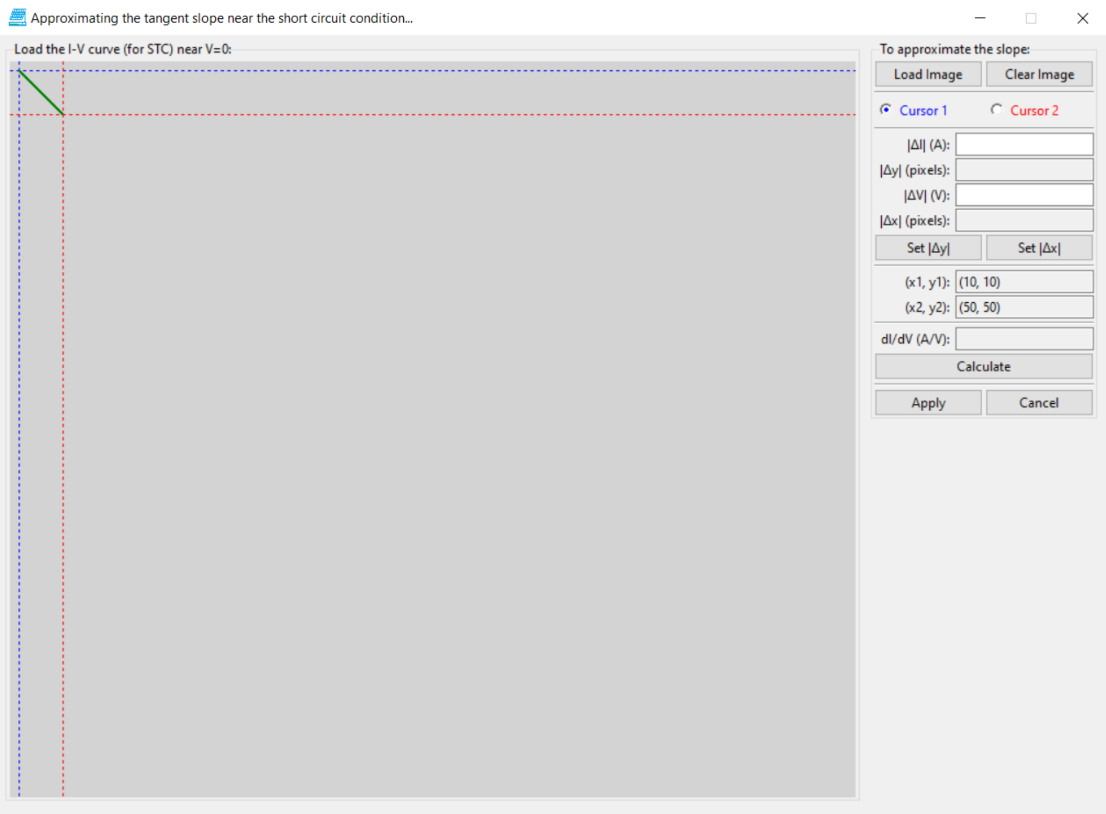

Fig. 3.9 The short circuit condition dI/dV window, number 1

Click the "Load Image" button to load the previously saved marked and enlarged I-V curve plot near the short circuit condition. Because 1 pixel on the figure shown on the screen does not necessarily represent 1 A or 1V, the user needs to specify some additional information about how much current or voltage does a given length on the figure represent. This is easily done as explained in this section.

The cursor can be moved by choosing the active cursor, left clicking and dragging the mouse in the figure's area.

Move the cursors to the locations shown in Fig. 3.10. Click the "Set |Δy|" button. This captures the vertical distance between the two cursors. Because this amount of distance represents 1.0 A, enter 1.0 in the "|ΔI| (A):" text box. Now the window should look like Fig. 3.10. Note that because the user may make a different screen capture near the short circuit condition than the one shown in Fig. 3.10, the |Δy| distance in pixels that the user gets may be different than the one (150) shown in Fig. 3.10. Also note that because this distance is captured by moving the cursors manually, each time the user tries to get this distance using the same figure, the distance that is captured may also appear slightly different. However, this should only affect the extraction results slightly.

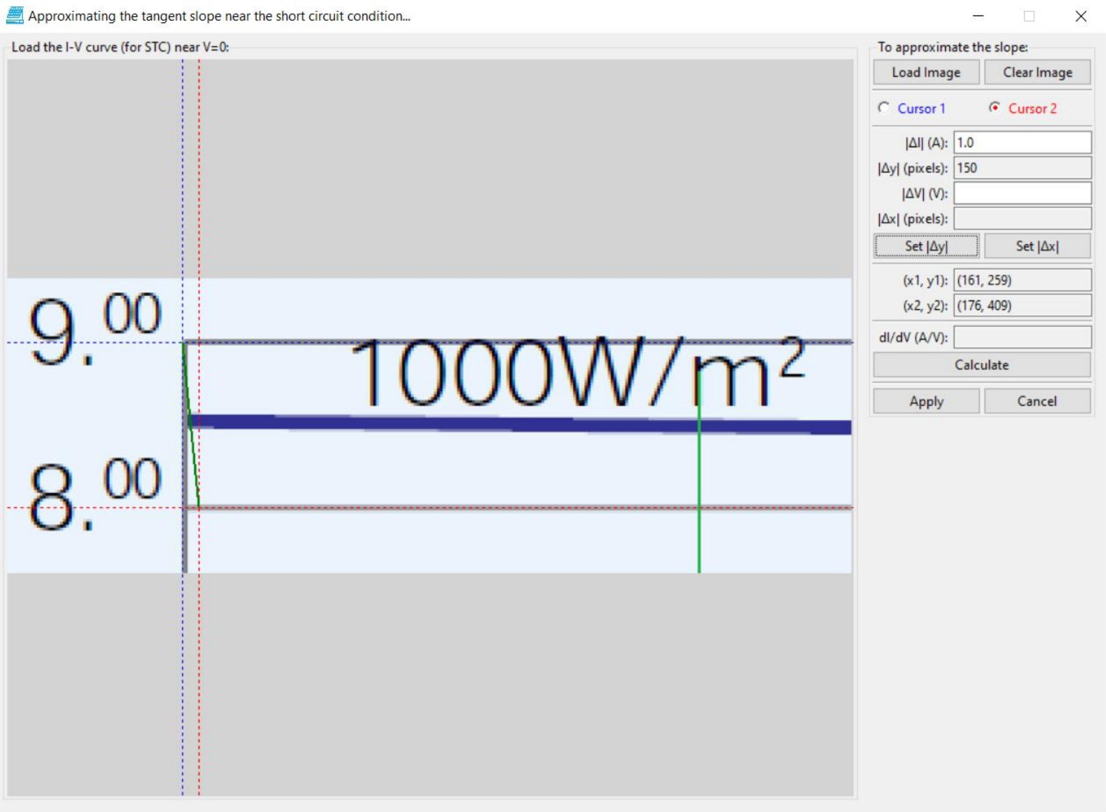

Fig. 3.10 The short circuit condition dI/dV window, number 2

Now, move the cursor such that they look like the ones shown in Fig. 3.11, and the green solid line connecting the two cursors should approximate the tangent of the I-V curve.

Click the “Set |Δx|” button the capture the horizontal distance between the cursors. Enter 10.0 in the text box for “|ΔV| (V):” because this horizontal distance represents 10

V as the mark made earlier indicates the 10 V tick mark on the horizontal axis. The window should look like Fig. 3.11.

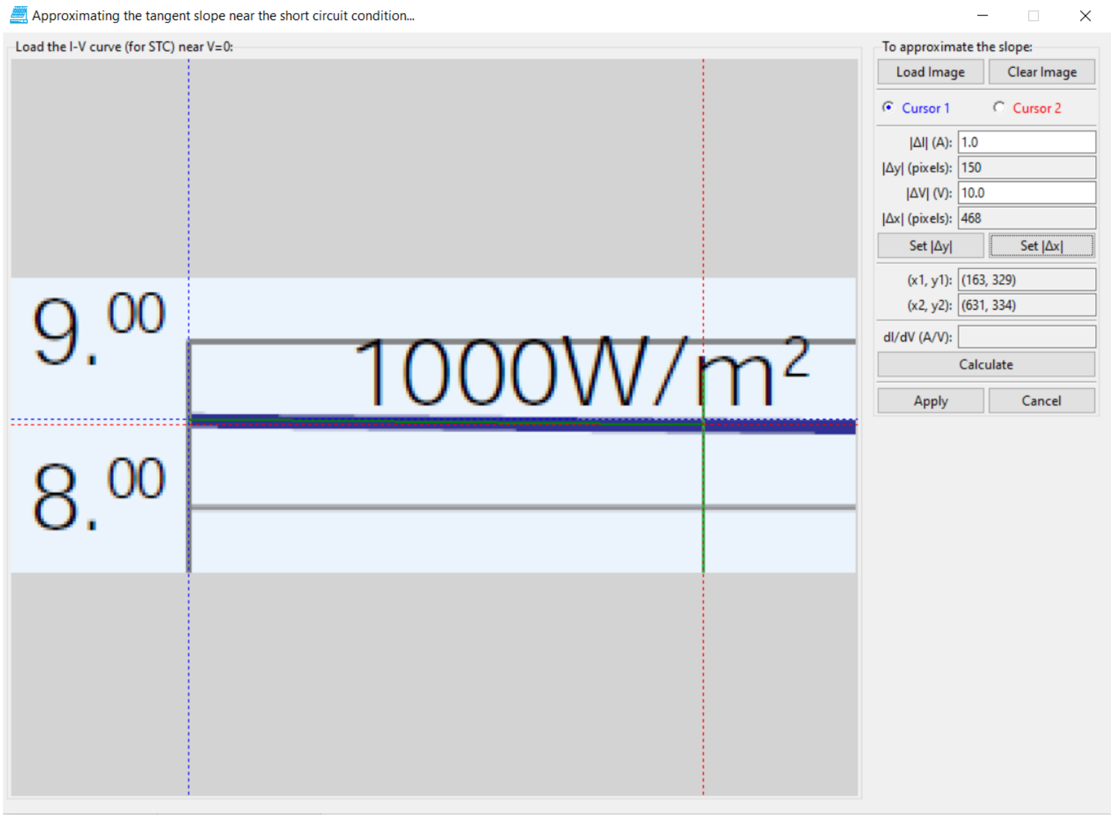

Fig. 3.11 The short circuit condition dI/dV window, number 3

Click the "Calculate" button, and the approximated slope of the tangent near the short circuit condition is obtained, shown in Fig. 3.12. Click the "Apply" button to accept the approximated value of dI/dV or redo the previous steps until a value is accepted by the user. If the user clicks the "Apply" button, the approximated value of dI/dV should appear in the main window.

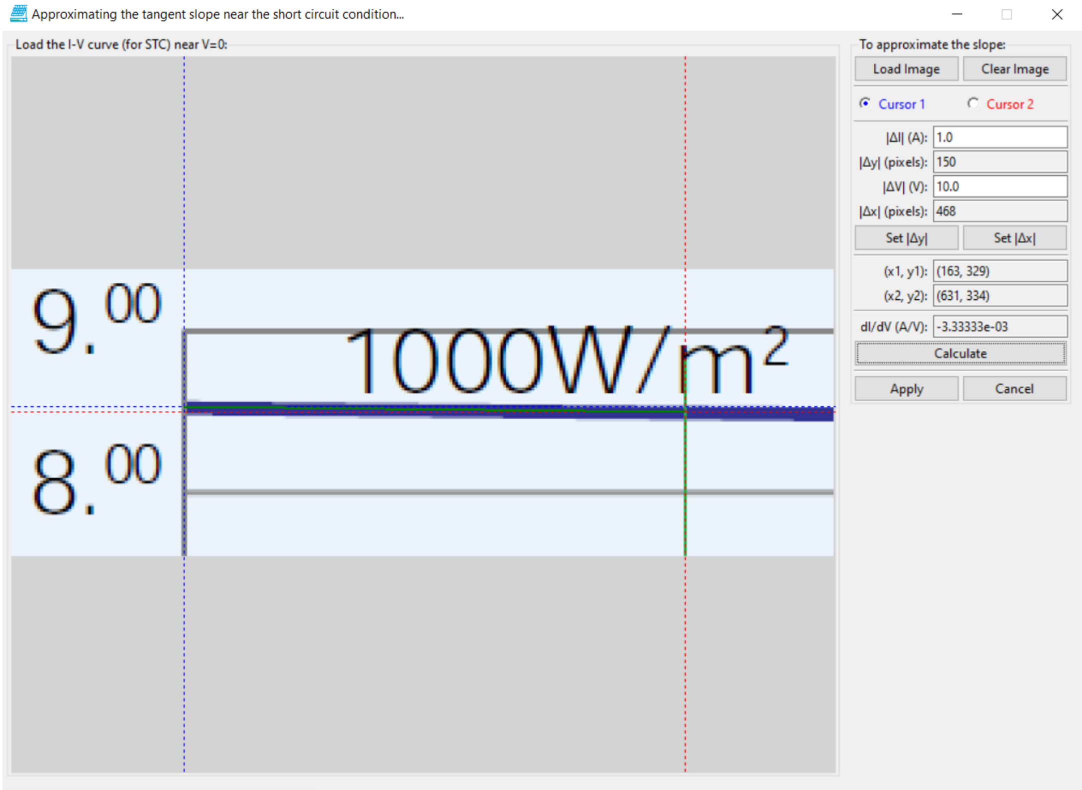

Fig. 3.12 The short circuit condition dI/dV window, number 4

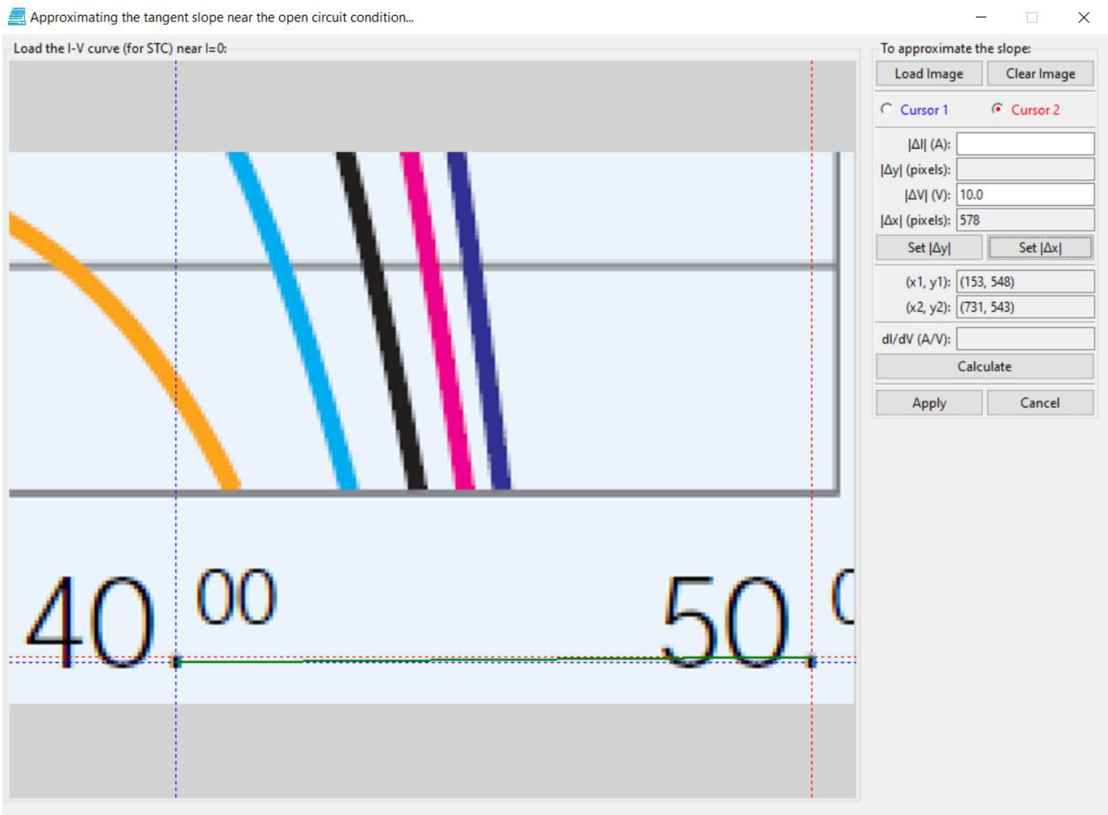

Fig. 3.13 The open circuit condition dI/dV window, number 1

The procedure for approximating the slope of the tangent of the I-V curve near the open circuit condition is very similar. Click the “Get” button corresponding to the open circuit condition and load the figure that was saved earlier. First, the user needs to enter “|ΔV| (V):” and capture |Δx|, shown in Fig. 3.13.

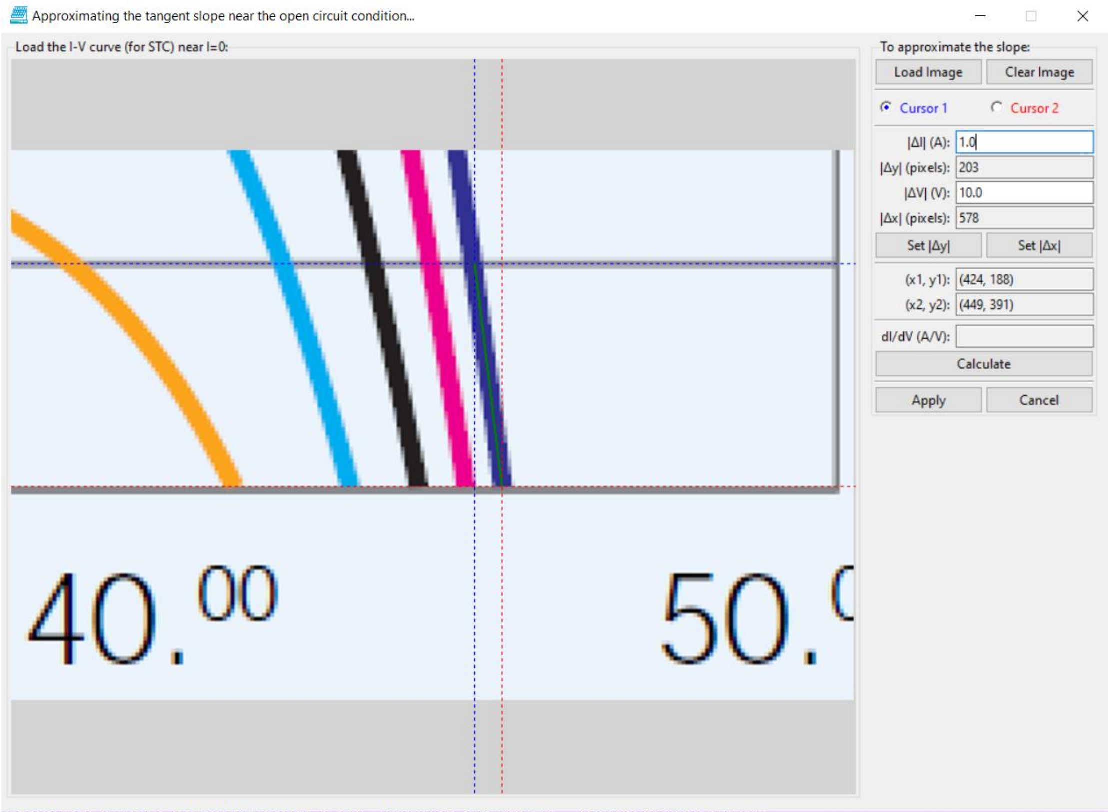

Fig. 3.14 The open circuit condition dI/dV window, number 2

Then approximate the tangent using the two cursors, shown in Fig. 3.14. Don’t forget to enter 1.0 in the “|ΔI| (A):” text box and capture the vertical distance between the two cursors by clicking the “Set |Δy|” button.

Click the “Calculate” button, and the window should look like Fig. 3.15, then click the “Apply” button to apply the approximation.

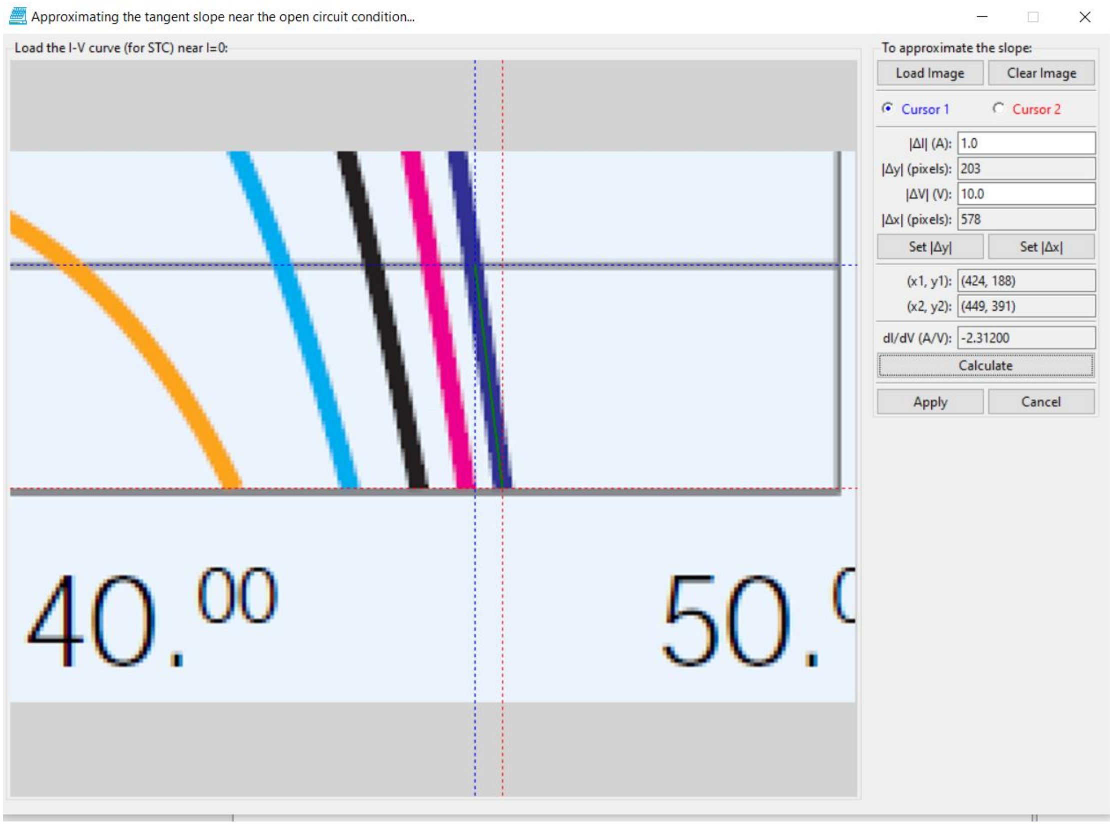

Fig. 3.15 The open circuit condition dI/dV window, number 3

Now, the main window should look like Fig. 3.16.

Note that even if the user uses different screen captures of the I-V curve to approximate the dI/dV, the dI/dV values obtained should be very similar to the ones shown in Fig. 3.16.

Also note that a very well manufactured solar panel's I-V curve should be almost flat near the short circuit condition. This corresponds to a very large shunt resistance described in section 2.3. If the curve is flat enough, capturing a non-zero slope of the tangent is difficult. To make the numerical calculation robust, if the curve is identified by the application as too flat, the application will suggest the user to use 1×10^{-6} as the slope of the tangent near the short circuit condition. This will not practically affect the I-V curve obtained using the equivalent circuit parameters. As an analogy, when designing a signal amplifier for a voltage signal source that has a series resistance of

0.1 Ω, changing the input resistance of the amplifier from 1 MΩ to 10 MΩ alone makes no practical difference in the performance of the amplifer.

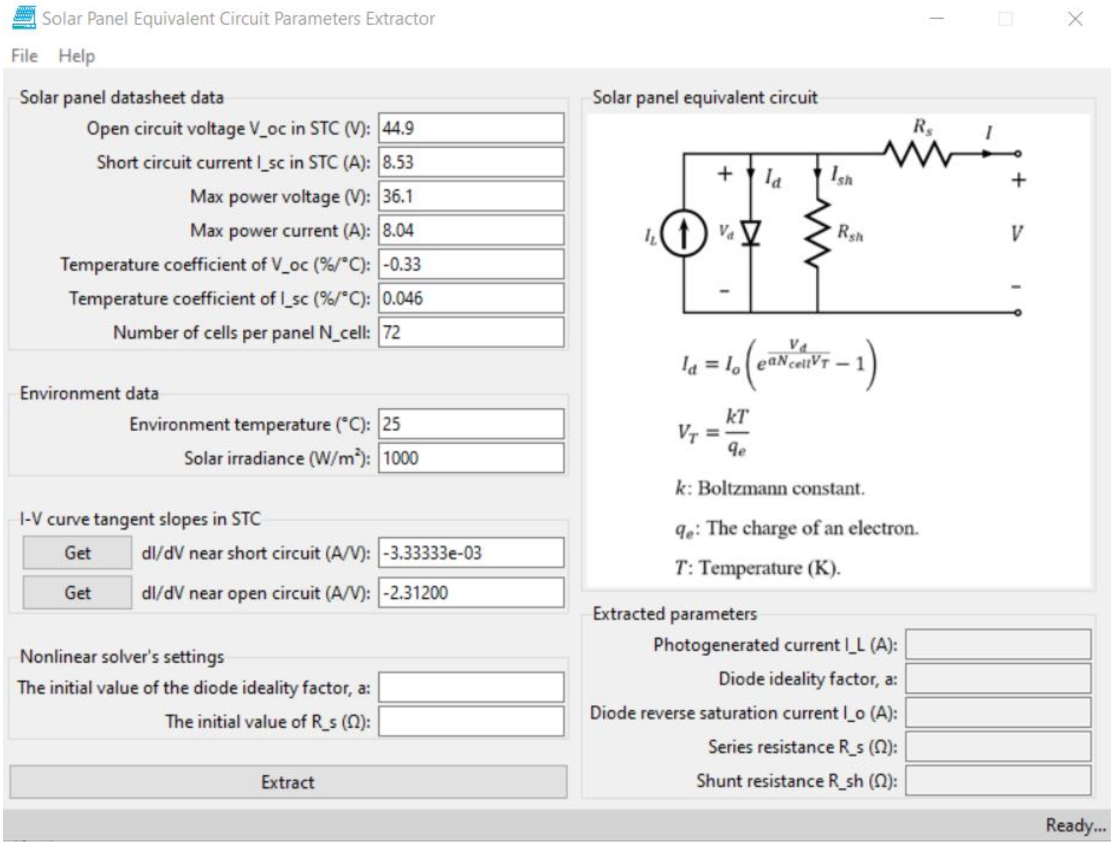

Fig. 3.16 The main window with dI/dV values

3.5 Step 5. Provide the initial values for the nonlinear solver and extract

As explained in Section 2.3.4, the a nonlinear solver is needed to extract the parameters, a, I_o, and R_s. Initial values must be provided to the nonlinear solver. Since a and R_s's ranges are easier to guess, the initial values of a and R_s should be provided by the user. The initial value of I_o is calculated using (2.7) internally by the application.

Any values between 1.0 and 1.5 are good initial values for a, and R_s is usually smaller than 0.5 Ω. Enter 1.2 and 0.2 as the initial values in the text boxes in the GUI. The window should look like Fig. 3.17.

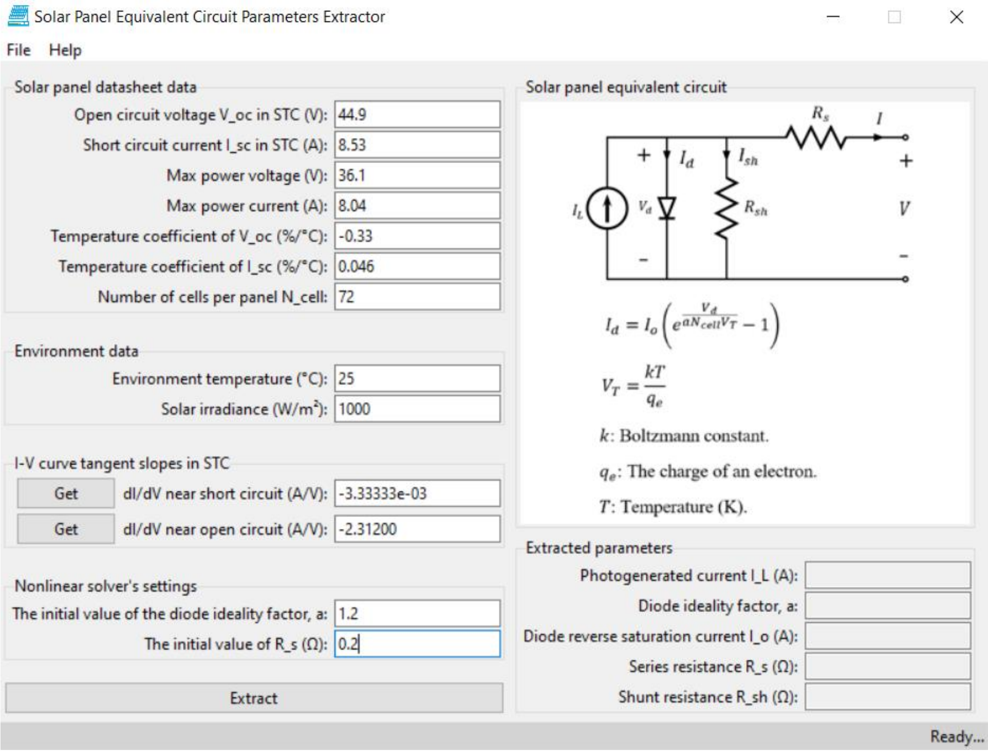

Fig. 3.17 The main window with initial values

3.6 Step 5. Extract and save the results

Now, the user is ready to extract the equivalent circuits parameters. Click the "Extract" button. The extracted parameters are shown in the section at the bottom right corner of the window, shown in Fig. 3.18.

How can the user know how accurate is the solution obtained using the nonlinear solver? The solution accuracy is represented by the mismatch errors of the equations (2.11) - (2.13). The mismatch errors are defined as the absolute value of the RHS of these equations. Ideally these mismatch errors should all be zero.

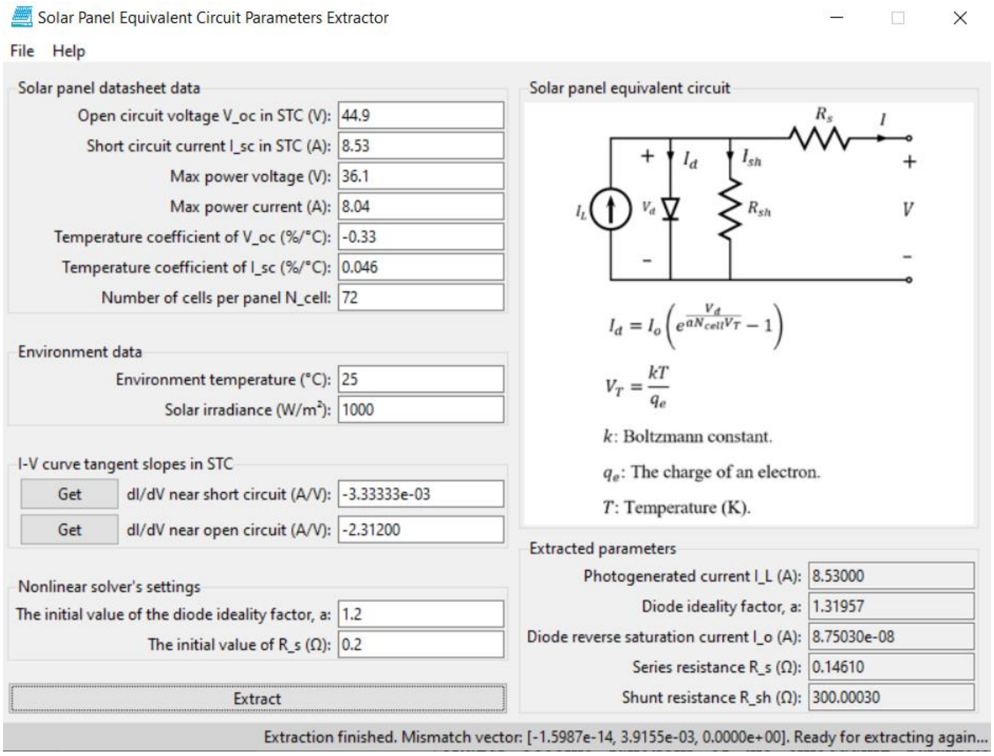

Fig. 3.18 The main window with extracted parameters

In Fig. 3.18, the mismatch errors are shown in the bar at the bottom of the window. Using scientific notation, the largest mismatch error is for (2.12), and it is 3.9e-3 (A). Practically this error can be ignored since that equation is for the optimal operating point where the optimal current is 8.04 A, so that the relative error is on the order of 0.5%.

As a summary, the extracted parameters are shown in Table 3.1 using scientific notation for I_o.

Table 3.1 Extracted parameters for TSM-290 PC/PA14

I_L (A)	8.53
a	1.31957
I_o (A)	8.75E-08
R_s (Ω)	0.1461
R_{sh} (Ω)	300.0003

The user can save the extracted parameters as a JSON file by using the "Save" button in the "File" menu, or simply by pressing the hot key "Ctrl+S", shown in Fig. 3.19.

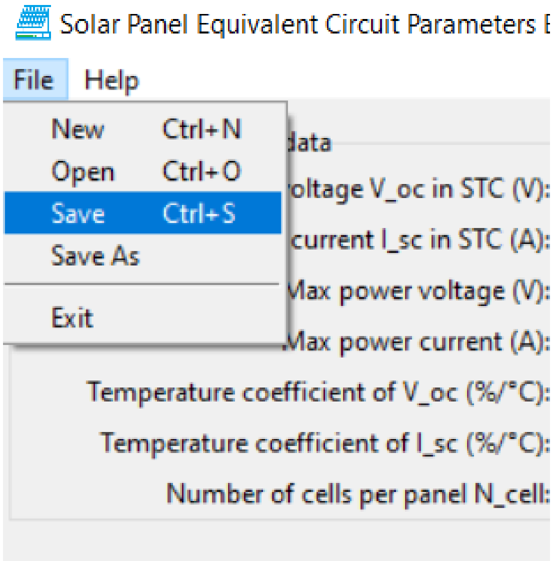

Fig. 3.19 Save the extracted parameters

After extracting the equivalent circuit's parameters, the user may hope to validate the results. The validation method is presented in the next chapter.

4 VALIDATION

The solar panel equivalent circuit is usually used in the simulation as an intermediate step for designing the power electronic converters for the solar panels and the corresponding controllers. It is important that after using the extracted equivalent circuit parameters, the user can approximate the I-V curve printed on the datasheet in the simulation software, so that the equivalent circuit can be used to represent the real solar panel. Therefore, the validation of the extracted parameters is needed.

The user can choose from many simulation software such as MATLAB's Simulink, PLECS, PSpice, LTspice and Scilab's XCOS, to perform validation, but in this chapter, Scilab and XCOS are used because it is free and open source. The validation is performed by duplicating the I-V curve and generating the P-V curve using the equivalent circuit with the parameters extracted using the application.

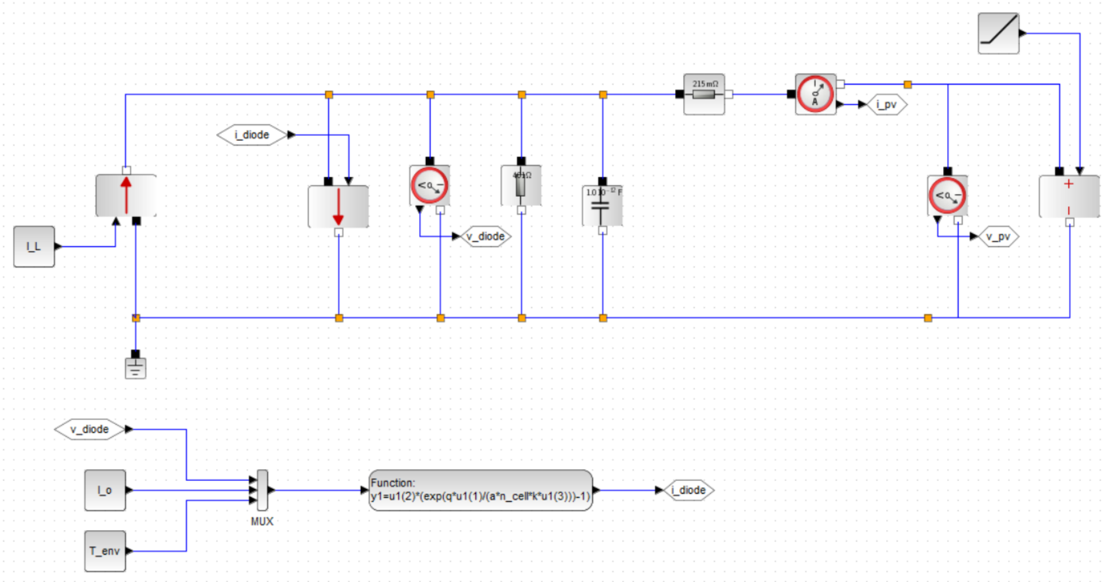

Fig. 4.1 Equivalent circuit diagram in XCOS

4.1 The equivalent circuit diagram in XCOS

The equivalent circuit diagram can be easily drawn in XCOS as shown in Fig. 4.1. The capacitor with 1E-12 F capacitance is put to eliminate the "algebraic loop" error in

XCOS, but it has no practical effect on the simulation results. The output diagram for the I-V curve and the P-V curve is shown in Fig. 4.2.

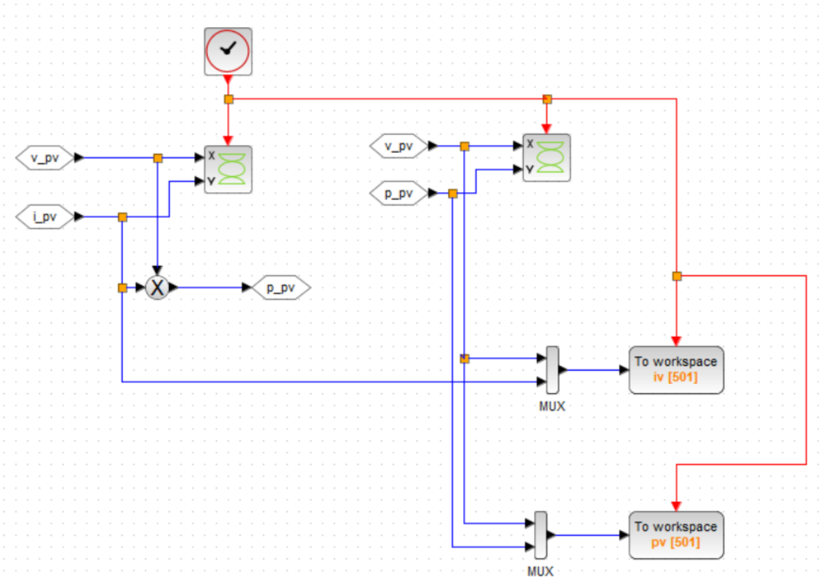

Fig. 4.2 Output diagram in XCOS

The parameters are set as shown in Fig. 4.3

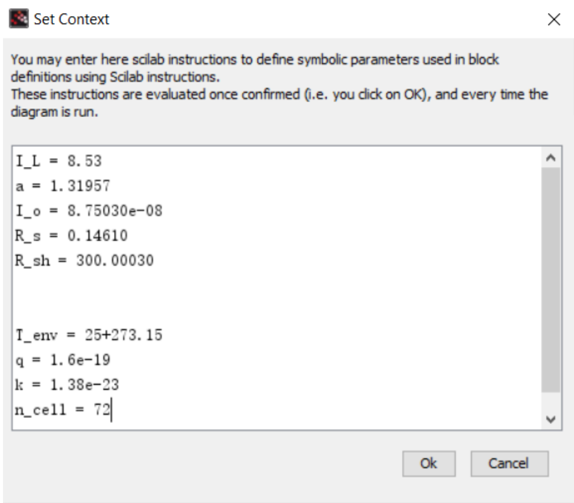

Fig. 4.3 Set parameters

4.2 Plot the I-V curve and the P-V curve

After running the simulation in XCOS, the I-V curve and the P-V curve can be plotted using Scilab, and they are shown in Fig. 4.4 and Fig. 4.5.

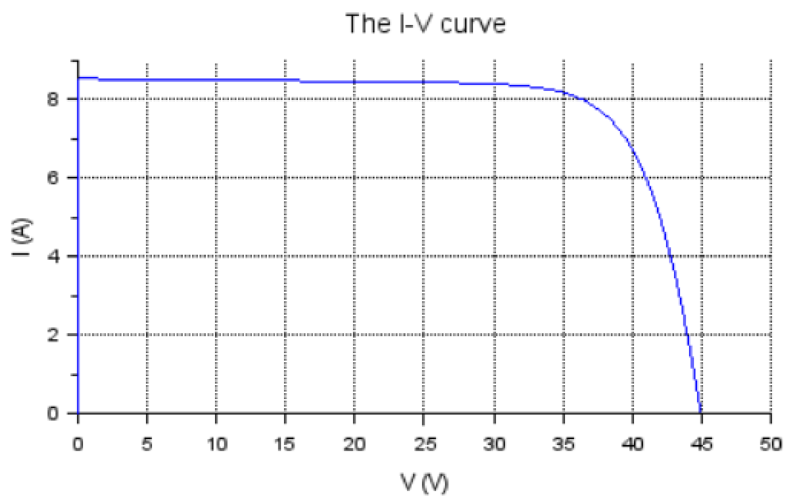

Fig. 4.4 The I-V curve using extracted parameters

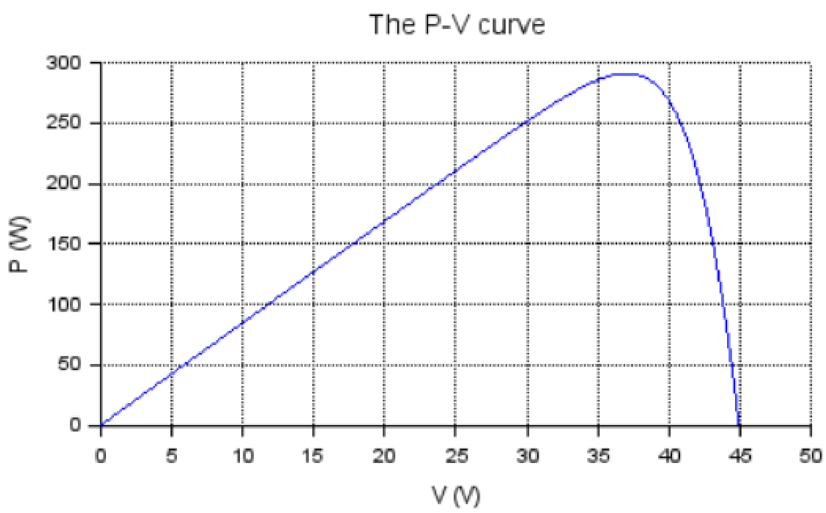

Fig. 4.5 The P-V curve using extracted parameters

4.3 The validation of the extracted parameters

At first glance, the I-V curve is duplicated well enough. The user is encouraged to use some graphical processing software to overlap the I-V curve in Fig. 4.4 onto the I-V curve printed on the datasheet to compare more closely, however, there is another way to quickly examine the accuracy of the extracted parameters: evaluating the optimal operating point shown on the P-V curve and its difference with the point shown on the datasheet.

When extracting the parameters using the nonlinear equations in section 2.3.4, the condition that at the optimal operating point (the maximum power point),

$$\left.\frac{dP}{dV}\right|_{maximum\ power\ point} = 0 \tag{4.1}$$

is never used. Equation (2.12) simply states that the I-V curve should pass the point (I_{mp}, V_{mp}), but it never guarantees that the P-V curve has a peak at $V = V_{mp}$. Therefore, the user can evaluate how far is the optimal operating point shown on the P-V curve from that shown on the datasheet. The optimal operating point on the P-V curve is at $V = 36.75$ V and $P = 291.23$ W, shown in Fig. 4.6.

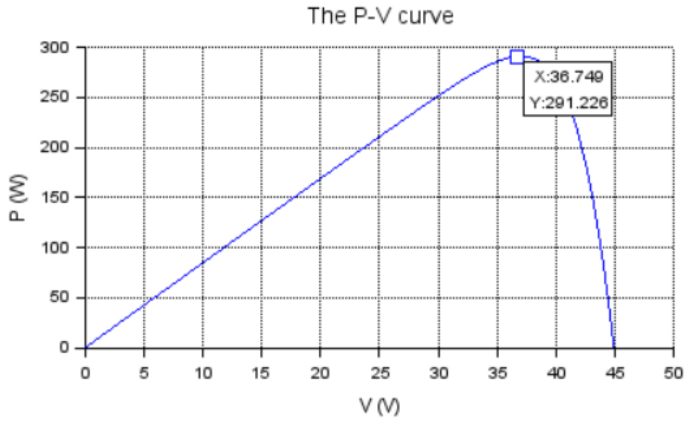

Fig. 4.6 The P-V curve using extracted parameters, maximum power point marked

The relative error between the optimal operating point voltages shown on the P-V curve and on the datasheet is 1.8%, less than 2%. The relative error between the peak power values shown on the P-V curve and on the datasheet is 0.42%, also less than 2%. Because the graphical method used in the application uses some approximation assumptions and the approximations of the slopes of the tangents of the I-V curve are partially made manually, such errors cannot be eliminated. However, such errors that are within 2% are negligible in the initial design stage of the power electronic converters.

5 CONCLUSIONS

5.1 Conclusions

This introduction and user manual presents to the users the mathematical background for extracting the solar panel equivalent circuit's parameters using a graphical method, the detailed steps for using the application, and the ways to validate the extracted parameters. It has been shown that the relative errors for the optimal operating point voltage and the peak power output obtained using the application are all below 2% for the TSM-290 PC/PA14 solar panel.

Given the good accuracy and the fact that this application is free and open source, it would be unfair to mention some limitations of the graphical method itself. The graphical method presented in Section 2.3 is only applicable when the I-V curve is given on the datasheet. If for a specific solar panel type, the I-V curve is not given, the nonlinear regression method is still needed to extract the equivalent circuits parameters using the measurements of the voltage and current at the terminal of the solar panel. However, for such an application using nonlinear regression, a GUI is not necessary, and a command line application might be more suitable.

5.2 Future development plans

At this moment, there are two aspects where improvements of the application can be made.

First, the mismatch error for (2.12) is still considered larger than ideal by the author. The error may be caused the fact that the fsolve function in SciPy uses a numerical method to obtain the Jacobian. Such a numerical method to obtain the Jacobian may not be robust enough for this particular application.

The solution to this conjectured problem is to develop a Newton-Raphson solver that uses the Jacobian provided in a closed form. Given the development time of this application is limited, developing a nonlinear system solver was not planned, but it may be necessary in the future.

Second, the solid segment connecting the two cursors in Section 3.4 is dark green by default and cannot be changed by the user. This, however, can be inconvenient if the contrast between the segment and the curve whose tangent is to be approximated is not strong enough. The user may not tell the difference between the solid segment and the underlying I-V curve. There is a need for a module to let the user customize the color of the solid segment.

5.3 Disclaimer

This work is not sponsored by any individuals or organizations. It is just a personal project of the author.

The author strongly suggests the user do not use this application on critical projects where if some unknown failure related to the application occurs, the consequences may be severe (for example, deaths, injuries, property loses), such as projects related to medical science, health care devices and hospitals, etc. The author is not responsible for any consequences caused by using this application, and for any misuse of this application, either.

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